The Dynamic Interaction of Climate, Vegetation, and Dust Emission, Mojave Desert, USA

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Abstract: Sparsely vegetated drylands are an important source for dust emission, but little is known in detail about dust generation in response to timing of precipitation and the consequent effects on soil and vegetation dynamics in these settings. This deficiency is especially acute at intermediate landscape scale, a few tens of meters to a several hundred meters. It is essential to consider dust emission at this scale, because it links dust generation at scales of grains and wind tunnels with regional-scale dust examined using remotely sensed data from satellites. Three sites of slightly different geomorphic settings in the vicinity of Soda (dry) Lake were instrumented (in 1999) with meteorological and sediment transport sensors to measure wind erosion through saltating particle detection during high winds. Changes in vegetation in close proximity to the instrumented sites were bi-annually documented through measurements of plant type, cover, and repeat photographic imagery. A succession of dry and wet years has allowed documentation of the profound influence of precipitation-driven annual plant growth (both living and remnant) on variability in dust emission. High levels of precipitation (relative to our period of record) during late winter/early spring 2001 stimulated heavy localized growth of annual grasses, shutting down dust emission at the sites within a period of three months. The year 2002 was very dry with little precipitation or plant growth, yet remnant dead grasses from the previous year continued to stabilize the surface and suppress dust emission for about three months. Modest renewal of particle saltation occurred in late 2002. During early spring 2003, all of 2004, and winter/spring 2005, heavy precipitation stimulated excessive localized plant growth including an extraordinary bloom of an invasive mustard species at one site and mediterranean grass at another. The three-year succession of strong annual vegetation growth dramatically suppressed particle saltation and associated local dust emission. In 2006 and through most of 2007, relatively low precipitation, less vigorous vegetation growth, and gradual disintegration of remnant vegetation cover initiated a strong resurgence of particle saltation by spring 2007. This

resurgence came to an end when several heavy precipitation events in the fall of 2007 stimulated vegetation growth that shut down dust emission within a period of about two months. The stable, non-emissive conditions, maintained by stands of remnant vegetation continued through summer 2008. The nine-year record at these sites spans multiple cycles of wet and dry conditions, thus allowing a detailed analysis of the lags and mediating influence that precipitation driven annual plant growth and decay exerts on dust emission in sparsely vegetated drylands.

Introduction

Most atmospheric dust is emitted from a variety of dryland settings, including many kinds of geomorphic surfaces having sparse vegetation, dry-lake basins, and dry riverbeds [Goudie and Middleton, 2006]. Human activities may influence any of these and other settings (e.g., for agricultural fields) to promote or suppress dust emission. Interest in the causes and effects of dust generation and deposition has increased greatly in recent years, with growing awareness about relations between dust and landscape evolution [Swap et al., 1992; Chadwick et al., 1999; Vitousek et al., 2003; Reynolds et al., 2006; Wang et al., 2006; McTainsh and Strong, 2007], about the effects of dust on air quality and human health [Vedal, 1997; Samet et al., 2000; Plumlee and Ziegler, 2003; Cook et al., 2005], and about potential influences of atmospheric dust on climate and hydrology [Wood and Sanford, 1995; Harrison et al., 2001 ; Painter et al., 2007]. Improved knowledge of the important effects of dust on natural and human environments will come from a more complete understanding of the conditions of contemporary dust emission. Such understanding will lead to an enhanced ability to anticipate future amounts, sources, and contents of atmospheric mineral dust as climate and land surfaces undergo changes at a variety of time scales, from seasons to decades.

Despite the importance of knowing the causes of dust emission that give rise to significant dust plumes, only limited knowledge exists about the linkages among sediment availability, geomorphic settings, and soil moisture. For example, temporal aspects of dust emission in response to vegetation change in sparsely vegetated landscapes have received little attention [see Raupach, 1992; Wolfe and Nickling, 1993;Okin and Gillette, 2001; Zender et al., 2003; Okin, 2008]. In these settings, the processes and timing of dust generation appear to vary in response to the amount and timing of precipitation and the consequent effects on vegetation but in ways that would be better understood with more comprehensive field documentation. This gap in understanding is especially acute at the scale of geomorphic surfaces, on the order of a few meters to several hundred meters. It is essential to consider dust emission at this scale, because it links dust generation at scales of eolian particles [Marticorena and Bergametti, 1995] and wind tunnels [Gillette et al., 1980; Nickling and Gillies, 1989;] with regional scale dust emission commonly examined using remotely sensed data from satellites [Prospero et al., 2002].

To improve knowledge about dust emission, we undertook investigations of dust emission from sparsely vegetated, low-relief surfaces in the central Mojave Desert (USA)(fig. 1). At three study sites, and over a period of nine years, we collected measurements of meteorological conditions, soil moisture, wind erosion, and vegetation change. During the experiments, perennial vegetation, primarily shrubs and forbs, persisted with greatly varying degrees of plant cover. Two of the sites were highly vulnerable to the growth of annual plants, with consequent suppression of eolian activity. Moreover, one of these sites experienced a first-time (over our period of record) invasion of an alien annual plant, and the other experienced unprecedented growth of an established alien annual grass. Vegetation changes and eolian suppression at the third site occurred at a similar temporal scale, but with greatly reduced sediment loads and less vigorous vegetation growth. Such a large range of vegetation changes provided the opportunity to examine spatial and temporal interactions among eolian activity, perennial and annual vegetation, and climatic variability (including antecedent precipitation and soil moisture). The results of this study point to the importance of annual plant growth and demise as controls on dust emission from sparsely vegetated drylands.

Characteristics of the study area

The Mojave Desert of southern California and Nevada and southwestern Utah is characterized by its hot climate, fall- and-winter-dominant precipitation, sparse summer rain, and specific plant communities [MacMahon and Wagner, 1985]. Mean annual precipitation ranges about 34-310 mm, about 60-90% of which comes during winter [Hastings and Turner, 1965; Hereford et al., 2006]. Most of the Mojave Desert is dominated by perennial plants, mostly *Larrea* (creosote) and *Ambrosia dumosa* (bursage) [Shreve, 1942; MacMahon and Wagner, 1985], which provide about 20 % vegetation cover on average [Rowlands et al., 1982]. In another assessment using remotely sensed data (Moderate-Resolution Imaging Spectroradiometer Enhanced Vegetation Index, MODIS-EVI at 250-m resolution), Wallace et al. [2008] documented cover of perennial vegetation in the Mojave Desert, with most (90%) of the desert having less than 30% cover. Non-erodible elements, such as bedrock, coarse debris on alluvial fans, deeply dissected terrain, and dense vegetation make about 85% of desert surfaces stable against wind [Wilshire, 1980].

Interplant areas are commonly occupied by physical crusts and biologic soil crust [Rosentreter and Belnap, 2003], or by annual plants when antecedent precipitation is sufficient [Beatley, 1969; MacMahon and Wagner, 1985]. The assemblage and density of annual plants are further controlled by soil type and many kinds of surface disturbance that includes fire, grazing, and roads [D'Antonio and Vitousek, 1992;

Brooks and Berry, 2006; Brooks and Minnich, 2006], as well as elevated atmospheric CO_2 that appears to favor exotic annual grasses [Smith et al., 2000].

Regional climatic controls on dust emission from the Mojave Desert

Analysis of the frequency and diurnal variation of dust storms in the United Statesidentified deserts in southern California as the dustiest region in states bordering the Pacific coast [Orgill and Sehmel, 1976]. For this analysis, dust storms were detected on the basis of decreases in visibility at airports. Seasonal atmospheric circulation typically focuses most dust emission during the months of November through May when the track of winter storms commonly traverses the Mojave Desert [Changery, 1983)]. Within this period, based on visibility data at meteorological stations, most dust-emission events occur during the windiest periods of February, March [Brazel and Nickling, 1987; Bach et al., 1996**;** Lyles, 1983]. Eastward movement of jet-stream troughs passing across the Mojave Desert commonly generate strong winds that may produce dust plumes directed toward the northeast, but wind direction in such troughs, combined with topographic influence, also create strong, dust-laden northerly and southerly winds. Another recurring phenomenon, typically between October and February, is the Santa Ana wind that is produced over the Mojave Desert, especially west of our study area. These easterly winds are generated when an intense high-pressure system stalls north of the Mojave Desert. This high-pressure system and a low-pressure system just off the California coast combine with topographic focusing to create intense wind events. Such wind events commonly create west-bound dust plumes, leaving records of dust deposition in marine sediments and in soils of the Channel Islands [Muhs et al., 2007, 2008]. The lack of summer dust events from the Mojave Desert can be attributed to low wind speeds associated with normal anticyclonic circulation aloft that dominates the region [Changery, 1983].

Characteristics of the study sites

Three study sites in the vicinity of Soda (dry) Lake in the central Mojave Desert (fig.1) were chosen for monitoring of wind erosion in relation to climatic variability and vegetation change using meteorological and wind-erosion instruments and repeated vegetation-plot measurements. Selection of the sites was made on the basis of observed evidence for dust emission: (1) satellite observations of the regional dust storm of April 23, 1997, and (2) evidence of scouring and soil loss by wind erosion at each site [Reynolds et al., 2003]. The sites comprise slightly different geomorphic settings, but their surfaces were similar in consisting dominantly of alluvial and sand-sheet deposits that contain mainly sand and silt in varying amounts. Such terrain (mixed alluvial and eolian surfaces) makes up about 35% of the Mojave Desert [Stoffer, 2004].

Our study sites showed no evidence of human disturbance, either before or during the experiments, that would have enhanced wind erosion. Moreover, we took all possible steps to minimize surface disturbance in the construction and maintenance of the meteorological sites. Some of the surrounding areas have been cut by roads. The Crucero site lies about 450 m from the edge of an off-road-vehicle (ORV) use area that abuts a designated Wilderness Area. We did not observe any connection between use of this ORV area and saltation activity/dust emission at the site. Thus, disturbance does not appear to be a factor in this study.

The Balch site, established November 1999, is located approximately 9 km southwest of Soda (dry) Lake playa (latitude, 35° 01.929'N; longitude, 115° 58.172'W), at an elevation of about 353 m. It is located on relatively level terrain in an area of obvious wind scouring, interspersed by areas of higher relief which appear stabilized by vegetation. A major wash (Kelso Wash) runs east-west approximately 54 m to the south, with a smaller wash trending northwest-southeast, approximately 35 m from the site. The area south of Kelso Wash is dominated by creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*) on a slightly sloping bajada of sandy soil, lightly armoured with loose gravel and cryptogamic soil crusts. By contrast, the area of the monitored site has a very different character; the soil appears to be predominantly eolian sand, silt and clay. When the site was first occupied, most of the creosote bush was dead, and no biologic soil crusts were observed.

The Crucero site, established March 2000, is located about 0.3 km north of the Union Pacific R.R. tracks at Crucero Hill (latitude, 35° 02.981'N; longitude, 116° 09.133'W), at an elevation of approximately 308 m. This location is within the boundary of late Pleistocene Lake Mojave, which existed from 22,000 to 8,700 years Bp, and about 7.5 km SSW of Soda (dry) Lake playa. The site is on the southern edge of the Mojave River fan-delta, just before it makes a northward turn into Soda Lake Basin, in the Mojave National Preserve. The site is characterized by low coppice-like mounds anchored by saltbush (*Atriplex* spp.), with intervening areas of wind-scoured ground. The site appears to be within a slight depression relative to the surrounding area. The area around the site is marked by mixed stands of creosote bush (*Larrea tridentada*) and saltbush, and is punctuated by occasional coppice dunes dominated by honey mesquite (*Propsopis glandulosa*), the nearest of which is 57 m from the site's center. Heavy rainfall during January and February 2005 caused flooding in the Mojave River and its anastamosing drainage system into the Soda Lake basin between Afton Canyon and the Soda Lake playa surface. The site was flooded for some period of hours to days. Evidence for the flooding comes from perched sediment deposits on instrumentation 10-20 cm above ground surface, abnormal albedo values from shortwave radiative reflection off of water, and persistent soil moisture values exceeding 50%.

The North Soda Lake site (NSL), established November 1999, is located on essentially flat terrain at an elevation of about 282 m, along the northeast margin of Soda Dry Lake playa (latitude, 35° 13.479'N; longitude: 116° 04.125'W). This location places the site well within the boundary of late Pleistocene Lake Mojave. As such, pluvial sedimentation and lake desiccation, as well as eolian deposition and erosion have influenced the soils here. These conditions helped influence the establishment of a Saltbush Scrub plant community dominated by *Atriplex* species. This community is transitional between the Alkali Sink Scrub community immediately bordering the playa to the west (dominated by inkweed, *Suaedu moquinii*), and the Creosote Bush Scrub community which covers the bajada slope to the east (dominated by creosote bush, *Larrea tridentata*). This sequence is typical of much of the terrain surrounding Soda (dry) Lake and is primarily related to alkali and salt tolerance, as well as tolerance to the poorly drained soils near the lake bed.

Methods

A variety of methods and instrumentation were employed in collection of the data presented here. A complete review and details of all instrumentation and field samplers is presented at the U.S. Geological Survey Southwest Climate Impact Meteorological Stations (CLIM-MET) website [http://esp.cr.usgs.gov/info/sw/clim-met/index.html]. Data collection is ongoing.
All meteorological sensors are monitored every 4 seconds with the exception of soil moisture which is sampled once per hour. The 4-second resolution measurements are averaged, or totaled in the case of

rainfall and Sensit particle impacts, and saved once per hour. In this chapter we further compile the data to represent weekly or monthly averages and totals. Environmental variables that are highlighted here include: rainfall totals which are collected using a Texas Instruments TE-525 tipping bucket; soil moisture which is measured using the TDR (Time Domain Reflectometry) method with a Campbell Scientific CS615 Water Content Reflectometer buried at approximately 10 cm depth; wind speed and direction which are measured with a R.M. Young 05103 wind monitor; and saltating particle impacts which are measured with a Sensit Company H7 model Sensit Erosion Monitor [http://www.sensit.com/]. All environmental data are stored on Campbell Scientific dataloggers and are collected manually twice per year or via a system of data telemetry in near real-time.

BSNE sediment samples are collected at three heights (15, 50 and 100 cm) above the ground surface with a Custom Products and Consulting, BSNE wind aspirated dust sampler [Fryrear, 1986,1995]. BSNE samples are collected four times per year at a minimum, and during high wind seasons, are sampled at higher temporal resolution. All samples are dried (if wet) and then weighed.

An instrument system that allows for automated remote digital images was deployed at Zzyzx Mountain (fig. 1) over a two-year period to capture dust emission from the three sites [Tigges et al., 2001]. Three cameras, one pointed to each of the three study sites, were programmed to take images when: (1) average windspeed at the site exceeded 5.4 m/sec over 15 minutes (one image every 15 minutes) or (2) Sensit activity reached 6750 counts in 15 minutes (one image every 15 minutes). In either case, radio signals communicated from a CLIM-MET site to the camera site, triggering photo collection based on one, or both, of the two environmental conditions. Stored digital photographs were periodically collected for examination of aeolian activity in the vicinity of the CLIM-MET sites.

Independent of the automated image acquisition, repeat photographs are taken at each site twice per year (fall and spring) during maintenance visits. A database of all repeat photography is available at the CLIM-MET repeat photography website [http://esp.cr.usgs.gov/info/sw/clim-met/photos/index.html]. In this chapter, we present a suite of photographs from the Balch site to illustrate the variability in annual vegetation cover.

Vegetation data for plot-percent coverage are collected twice per year, once in the spring and once in winter. All efforts were made to complete spring repeat photography and vegetation sampling contemporaneously, however, there were instances when the two collections occurred up to one month apart. Vegetation plots consisted of 4 m x 50 m areas for living/dead perennials (sampled in winter) and 1 m x 25 m areas (nested) for living/dead annuals and sticks and stones (sampled in spring). Sticks and twigs were measured as rectangles (length x width). Clasts > 0.5 cm across at the widest dimension were measured across the widest dimension and at 90° to that dimension for calculation as ovals. Plants (living or dead) were measured as height and as two diameters of canopy for calculation as ovals. For objects that crossed the plot boundary, only the portion inside the plot was measured. Understory plants were measured but are not included in the plant-cover data.

Results

Previous investigations have documented that dust emissions from desert surfaces are commonly caused by saltation of eolian sediment during high winds (> 5.0 m/sec) that bombard and break surface crusts, thereby releasing fine particles (dust) into the atmosphere [see Gillette, 1981]. At our study sites, moderate to high wind speeds that are greater than or equal to 5 m/ initiate particle movement. Using the digital images obtained by the camera system on Zzyzx Mountain and data from the CLIM-MET sites, we conducted tests over a two-year period to determine whether or not this was the primary process of dust emission at the study sites. Dust emission was commonly observed to be generated by high winds at the sites in conjunction with spikes in Sensit particle counts. An example of a significant wind-saltation-dust event on April 15, 2002 is shown in figure 2. Comparisons among wind strength, saltation measured by Sensit particle counts, and observations of dust emission from remote-camera photographs indicate that the particle-count record can be interpreted as a record of dust emission.

The time-series records of dust emission (on the basis of Sensit particle counts) from the three study sites are roughly similar (fig. 3). Periods of relatively high dust emission span early spring 2000 to late winter 2001, early spring 2002 to late winter 2003, and most of 2007. More than three years of very low dust activity followed spring 2003 at the Balch and Crucero sites. Inactivity during most of this interval is evident also for the NSL site. Note the use of different scales to show saltation activity at the NSL site when absolute amounts of particle movement is very low relative to activity at the other sites (fig. 3). The Balch site experienced particle impacts one order of magnitude higher than those at Crucero and typically more than two orders of magnitude higher than those at NSL (fig. 3);[http://esp.cr.usgs.gov/info/sw/clim-met/climetdata.html]. One departure from the similarities of the time-series records is seen in the renewal of saltation activity at the NSL site beginning in early 2006 seven to eight months prior to renewal at the other sites (fig. 3).

The windspeed data reveal a seasonal pattern with highest winds during late spring and early summer. There is very little interannual variability in wind speed at each site, and such variability does not correspond to differences in dust emission (fig. 3) [http://esp.cr.usgs.gov/info/sw/clim-met/climetdata.html]. Average monthly wind speeds are very similar at the three sites during the windy late spring and early summer period, typically 2.5 to 3.5 m/s. However, during late summer and early winter, monthly average wind speeds at Balch (about 2.5 m/s) are higher than those at Crucero and NSL (1.5 to 2.0 m/s) [http://esp.cr.usgs.gov/info/sw/clim-met/climetdata.html]. This seasonal difference in wind speed is a result of topographic funneling and less resistance due to sparse perennial vegetation coverage at the Balch site, and may contribute to its stronger saltation and eolian response.

A detailed evaluation of dust emission inferred from particle saltation, surface conditions, and meteorological factors is emphasized for the Balch site, because of its record of copious dust production at times and suppression during long spells. Relations among rainfall, particle counts, and soil moisture illustrate qualitatively the strong control of precipitation on dust emission (figs. 4,5). Particle counts at Balch were highest in the early part of the record when vegetation cover was low as a result of antecedent drought conditions [Bell et.al., 2000]. The highest Sensit-particle count of our record (7,783,191 impacts per month) occurred in May 2000. Contemporaneously (April 27 to May 30), the Balch BSNE collector (total of all 3 buckets) collected an average of 15.5 g of sediment per day, the second highest amount in the record. Two other periods of sustained dust production during most of 2002 and the first half of 2007 followed long intervals with little precipitation (figs. 4, 5).

Relatively high amounts of precipitation fell during winter 2001, from early 2003 to mid 2005, and the latter half of 2007 (fig. 4). As expected, soil moisture closely tracked precipitation. For example, strong rains in January-March of 2001 increased the soil moisture values to 10-20%, significantly higher than the average 5-7% at this site. Vegetation cover responded to the precipitation with increasing annual vegetation density typically following heavy precipitation periods by one to three months (Table.1; fig. 6). Dust production diminished greatly or ceased altogether following these three periods of relatively heavy precipitation and the consequent spread of annual plants (figs. 3, 4). Eolian activity remained at low levels for long intervals of time after these periods of annual plant expansion and growth. Remnant annual grasses from 2001 continued to stabilize the surface until March 2002 when bare ground (figs. 6,7), and decreasing soil moisture (fig. 7) led to a resurgence of saltation (fig. 7) and amount of trapped eolian sediment (fig. 5). The abnormally wet seasons of late winter and early spring during 2003, 2004, and especially 2005 produced annual plant growth, including in 2005 the vigorous appearance of the alien invasive Sahara Mustard (*Brassica tournefortii*) at Balch and exuberant growth of the established alien Mediterranean grass (*Schismus barbatus*) at Crucero (Table. 1). Total vegetation cover in April 2005 reached 77% at Balch and 71% at Crucero. Nearly all (99%) of this vegetation was living when sampled in April 2005 (Table. 1). By April 2006 all of the annual vegetation at Balch and Crucero was dead but still rooted, providing (37.1 % and 52.65 %) cover respectably (Table. 1). This remnant vegetation provided continued stabilization of the surfaces against wind erosion (figs. 3, 7). Although winter precipitation at the Balch site in 2006 was below normal and would have likely limited annual plant growth and promoted saltation and emission, surfaces produced very little sediment in the BSNE traps and very low particle counts (figs. 5, 7).

Vegetation responses to precipitation influx at Balch and Crucero are very similar except in April 2008 (Table. 1) when surface saltation at Crucero was much greater than Balch (fig. 3). Following little precipitation in 2006 and 2007, soil moisture at the Balch site declined. By February 2007 Sensit counts at Balch resumed at high levels (figs. 4, 7) and sediment capture in the BSNE increased to amounts comparable to 2000 and 2002 (fig. 5). The resurgence was short lived, however, with the onset of heavy precipitation in September 2007, at 62.3 mm the highest monthly total of our record and double the amount received at Crucero (27.9 mm monthly total) [http://esp.cr.usgs.gov/info/sw/clim-met/climetdata.html]. The heavy precipitation stimulated enough vegetation growth to shut down saltation and emission within two months (fig. 7). Continued precipitation through January 2008 maintained high soil-moisture levels (figs. 4, 7) bolstering another bloom of Sahara mustard (figs. 5, 6), (similar to 2005) while lesser rainfall at Crucero produced only moderate growth of annual grasses (Table. 1).

When Sahara mustard grew in abundance in 2005 and 2007-2008 at Balch, the large amount of vegetative material effectively stabilized surface sediments while the plants were alive. Sahara mustard is an annual herb (non-native and invasive in the Mojave) that develops woody flower stocks 10-100 cm tall from a basal rosette of leaves as much as 30 cm long [http://ucce.ucdavis.edu/datastore/detailreport.cfm?usernumber=12&surveynumber=182]. After the mustard died, its woody properties gave it more resilience to disintegration than the annual grasses at the Crucero site, and to some degree the NSL site. In April 2008, remnant Sahara mustard continued to stabilize sediments at the Balch site while the dead annual grasses at Crucero blew away and left the site vulnerable to saltation and emission (Table. 1) (fig. 3).

As at the Balch and Crucero sites, saltation at the NSL site shut down following high rainfall (2003-2005 and late 2007) due to subsequent growth of annual plants, primarily Mediterranean grass (Table. 1) (fig. 3). However, the amounts of saltation during dry periods and annual plant growth following wet periods were much reduced (one to two orders of magnitude) from the other two sites (fig. 3). The primary reason for this seems to stem from the hard-crusted, saline, pluvial, surficial sediments at the NSL site that resist both wind erosion during dry periods and invasion/establishment of significant amounts of annual plants during wet periods.

Discussion

Monitoring eolian activity at the sites in the central Mojave Desert reveals interrelations among dust generation, precipitation, soil moisture, growth of annual plants shortly following wet periods, and vegetation disintegration during dry periods. Whereas high wind events are the dominant driver of saltation and dust emission, emissive conditions prevail only when annual plants are sparse or absent. Results show that wind erosion and dust emission at two study sites (Balch and Crucero) are highly variable and that such variability is dominantly related to vegetation type and cover as influenced by the amount and timing of antecedent precipitation. Secondary controls on dust emission are availability of new sediment related to flood deposits at the sites and seasonally differential wind strength.

Although the Balch and Crucero sites exhibit very similar temporal patterns of dust emission, the Balch site is characterized by much higher saltation and dust emission activity. The surface at Balch is more vulnerable to wind erosion because it lacks surface crust, has extremely sparse vegetation cover (except in wet years), receives topographically funneled winds that are slightly stronger relative to Crucero and NSL, and receives a more frequent supply of alluvial sand that is likely involved in dust production. The vegetation community at the NSL site is mediated by highly saline soils and significant surface crusting and thus differs greatly from those at Balch and Crucero. These characteristics result in much lower saltation values, an order of magnitude less than at Crucero, and two orders of magnitude lower than Balch (fig. 3). The renewal of eolian activity at NSL during 2006, while Balch and Crucero sites remained relatively quiescent, was probably related to the local heavy rains in 2005 that delivered flood-derived sediment to the NSL site. This influx of sediment and relative lack of surface stabilizing annual vegetation (compared to Balch and Crucero) led to resurgence in saltation seven to eight months before the other sites (fig. 3).

Periods of sparse rainfall and low soil-moisture conditions at the Balch and Crucero sites have led to strong saltation activity and vulnerability to dust emission. The records show that at sites where annual plants respond quickly and advantageously to precipitation, emissive conditions typically shut down because of vegetation growth within two to three months (fig. 7). This cover of annual plants, even when dead, persists in the desert landscape as a stabilizing agent for varying amounts of time, ten months to three years depending on the amount and vegetation type and subsequent input of precipitation and further annual plant growth (figs 4, 5, 7).

In this chapter, data were derived from small plots, at which detailed observations and measurements of climatic factors, vegetation, and wind erosion were closely monitored over a nine-year period (2000-2008). Interpretations from these results can be compared with those derived from different approaches to elucidate dustiness in the Mojave Desert, including two notable studies [Brazel and Nickling, 1987; Bach, et al., 1996] based mainly on observations of visibility from widely separated meteorological stations. Brazel and Nickling [1987] examined temporal and spatial patterns of regional dust emission over the southern Great Basin Desert, the Mojave Desert, and the Sonoran Desert. Dust storm frequency was obtained from visibility data at 17 meteorological stations and compared with climatic data from these stations along with regional factors for drought [the Palmer Drought Severity Index, PDSI; Palmer, 1965; Mather, 1974; Karl and Knight, 1985] and climate [the Climate Factor of Chepil et al., 1962, 1963]. Bach et al. [1996] used hourly meteorological data from 23 stations in the Mojave Desert and Sonoran Desert of southern California to determine mean annual frequencies of dust events and dust storms during the period 1973-1994. These two investigations recognized that dust emission in the Mojave Desert (1) is highly seasonal with most emission during the late winter and spring, (2) exhibited high interannual variability generally associated with antecedent precipitation, and (3) was partly related in complex ways to plant dynamics, with significant additional influence from surface crusting and human disturbance. Correlation between frequency of blowing dust and mean annual precipitation was weak [Bach et al., 1996] or undetected [Brazel and Nickling, 1987]; however, correlation of blowing dust events with two winters' antecedent rainfall was much stronger [Bach et al., 1996]. Bach et al. [1996] concluded that winter annual plants in the Mojave Desert, germinated because of late-fall and early winter rainfall, helped to suppress dust emission by April when the plants reached maximum coverage and development [Bowers, 1987]. Our results confirm the interpretations by Bach et al. [1996] and detail the ways in which winter-germinated annual plants act as a buffer against dust emission, even when dead relict vegetation remains attached to the surface.

The relations among precipitation, vegetation, and dust emission have been noted in other desert areas of southwestern United States but with different timing because of contrasts in climatic setting. For example, a set of studies found that (1) high dust-storm frequency in spring and summer was related to low precipitation during the previous winter in southwestern Arizona [Nickling and Brazel, 1984] and (2) diminished summer dust generation followed sufficient winter and spring rainfall to increase desert vegetation cover [Brazel and Nickling, 1986].

Our results and those of others [Bach et al. 1996; Brazel and Nickling, 1987; Bowers, 1987; Schultz and Olster, 1995a] indicate the critical influence of annual plants on dust emission in the Mojave Desert and adjoining landscapes. Nevertheless, many other factors involving vegetation dynamics exert variable controls on eolian activity. One consideration centers on variable plant response to drought and moisture. In the northern Mojave Desert, vegetation communities and individual species do not respond similarly to drought [Schultz and Olster 1995b]. Thus, below-normal rainfall totals may not everywhere lead to reduced vegetation cover and do not necessarily promote increases in dust emission. Other factors include the forms and properties of individual plants and their spatial distributions. The mechanisms by which plants increase surface stability are related primarily to increases in surface roughness that increase the shear stress of wind on the ground. Shapes, sizes, and porosities (openness within a canopy) of individual plants combine to influence roughness. Additionally, plant cover may increase soil moisture through temporary shading, thus promoting development of crusts and soil [Wilshire, 1983], and root systems hold soil particles together. Moreover, the distribution of vegetation may focus or attenuate wind energy, thereby enhancing or diminishing wind-erosion vulnerability [Raupach, 1992; Wolfe and Nickling, 1993; Okin and Gillette, 2001; Okin et al., 2006; Okin, 2008]. Landscapes with spatially variable vegetation cover have higher susceptibility to dust emission than those with the same amount of evenly distributed vegetation [Okin et al., 2006]. Eolian transport and feedback processes and nonlinear thresholds (minimum gap sizes for wind erosion) related to the distribution of vegetation can affect saltation and suspension of eolian sediment operating at different scales, as well as the flow and distribution of precipitation runoff and infiltration [Rango et al., 2006; Snyder and Tartowski, 2006].

Our results on conditions that promote or suppress dust emission can also be compared with results from studies of aerosols in the Mojave Desert [Frank et al., 2007] and the western U.S. [Wells et al., 2007] to reveal many different sources and particulate-matter sizes of aerosols that include mineral dust and human-related air pollutants. Using primarily measurements of aerosol optical depth (AOD) determined from satellite imagery from March 2000 to October 2005, Frank et al. [2007] recognized seasonality of AOD over the Mojave Desert. Relatively high AODs in the region were observed during spring and summer when aerosols from Los Angeles basin and San Joaquin Valley flowed into the desert. Lower AODs during fall and winter were attributed to lesser amounts of human-related air pollution over the Mojave Desert due to a higher degree of wet deposition. Over the western U.S. from 2001 to 2004, Wells et al. [2007] interpreted variations in the amounts of deposited particulate matter less than 2.5 and 10 microns in diameter (PM2.5 and PM10, respectively) to reflect relatively high amounts of Asian dust transport during summer and sometimes spring, with lowest amounts typically during winter. Surface dust concentrations of local dust, however, simulated by the Navy Aerosol Analysis and Prediction System [Witek at al. 2007] also were anomalously high at times during the fall and winter [Wells et al., 2007].

Conclusion

Recent expansion of dust-related research such as satellite-based remote sensing and numerical modeling has greatly improved knowledge about dust sources, fluxes, processes, and effects at global and regional scales [Prospero et al., 2002; Zender et al., 2003; Zender and Kwon, 2005; Goudie and Middleton, 2006;

Mahowald et al., 2006]. In building on new advances in the arena of eolian activity-vegetation relations [Neff et al., 2005; Okin et al., 2006; Okin, 2008], more effort is still required to understand some fundamental conditions and processes that generate or suppress dust emission at scales useful for land management. The results of the current study may help bridge investigations at the scales of wind-borne particles and plants in our study area [MacKinnon et al., 2004] with recent monitoring to document physical and biotic change in the central Mojave using a mix of remote sensing methods [Chavez et al., 2002].

Results of this study document in detail the roles of vegetation dynamics in controlling dust emission from sparsely vegetated dryland. The importance of annual plants is especially profound. In the study area, annual plants responded rapidly to precipitation, with dense plant growth commonly following precipitation by only months and subsequently shutting down dust emission. Annual plants may have long-lasting effects as dead remnant cover. This lasting effect seems to be especially strong for grasses, such as brome, although exceptionally vigorous growth of forbs can produce similar results. In North America, several species of brome have undergone extensive invasion of native perennial grasslands and shrubland [Bradford and Lauenroth, 2006]. The conversion from native plant communities to landscapes dominated by alien annual plants is especially enhanced by fires in shrubland communities [Brooks and Berry, 2006; Brooks and Matchett, 2006]. We might anticipate variable dust-emission responses in areas that have been or will be dominated by alien annual plants. These responses depend on the compositions of invaded plant communities and on various factors of climate, soil, and disturbance.

The following few examples illustrate a possible range of dust-emission potential for landscapes affected by alien plant invasion. Dense invasion by annual grass of terrain long occupied by native plant communities having low vegetation cover and roughness along with soil texture favorable for dust production may decrease the wind-erosion vulnerability of some areas under climatic conditions characterized by sufficient precipitation to encourage annual plant growth every few years. Increasing levels of atmospheric CO_2 may further encourage the growth of annual plants [Smith et al., 2000]. Such areas may return to significant dust production only during relatively severe and long-term drought. In a contrasting scenario, conversion of shrubland, historically resistant to dust production because of vegetation-roughness characteristics, to annual grass might increase the potential for dust generationduring periods of extended drought. Landscapes that can resist plant invasion are certainly not immune from future increased dust generation. For example, climate models point to overall warming and drying of the American southwestern deserts over the next several decades [Seager et al., 2007]. If such changes occur and lead to diminished extent of perennial plant communities, dust emission from affected areas will likely increase.

During this experiment, periods of high precipitation led to vegetation growth and suppression of dust from the study sites. Nevertheless, many dust sources were active from other types of surfaces in the Mojave Desert while our instrumented areas resisted wind erosion. Such other dust sources included playas and dry lakes, dry riverbeds, dirt roads and off-road vehicle tracks, areas used for military exercises, as well as lands under construction for urbanization and other development. A comprehensive understanding of dust emission from regions such as the Mojave Desert requires assessment of many different geologic, geomorphic, and human-affected settings as potential dust sources considered with climatic and ecologic factors that promote or lessen eolian activity.

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Figure captions

Figure 1. Map of study area. Red squares denote locations of study sites.

Figure 2. Wind-driven particle saltation leading to a dust emission event at the Balch site. This event was captured at 1700 hrs Pacific Daylight Time by the Zzyzx Mountain digital camera during peak hourly average windspeed of 10.65 m/sec and 167,600 total hourly Sensit particle impacts. Total hourly particle impacts and average hourly windspeed are plotted by decimal hour. Each data marker (x or *) represents one hour.

Figure 3. Monthly total Sensit particle counts at the Balch, Crucero, and North Soda Lake sites. Numerals in parentheses (1-5) identify months when total values were orders of magnitude higher (and thus off scale) than the rest of the record at each site. Total particle count values for these months are, (1) 6.21×10^6, (2) 7.78×10^6, (3) 5.76×10^6, (4) 1.48×10^6, (5) 3.86×10^4. NS designates (Not in Service), the station had not been installed yet.

Figure 4. Time-series of monthly total rainfall and Sensit particle counts, as well as monthly average soil moisture and windspeed at the Balch site. Letters (A-I) correspond to time periods described in the text and Figures 5 and 6.

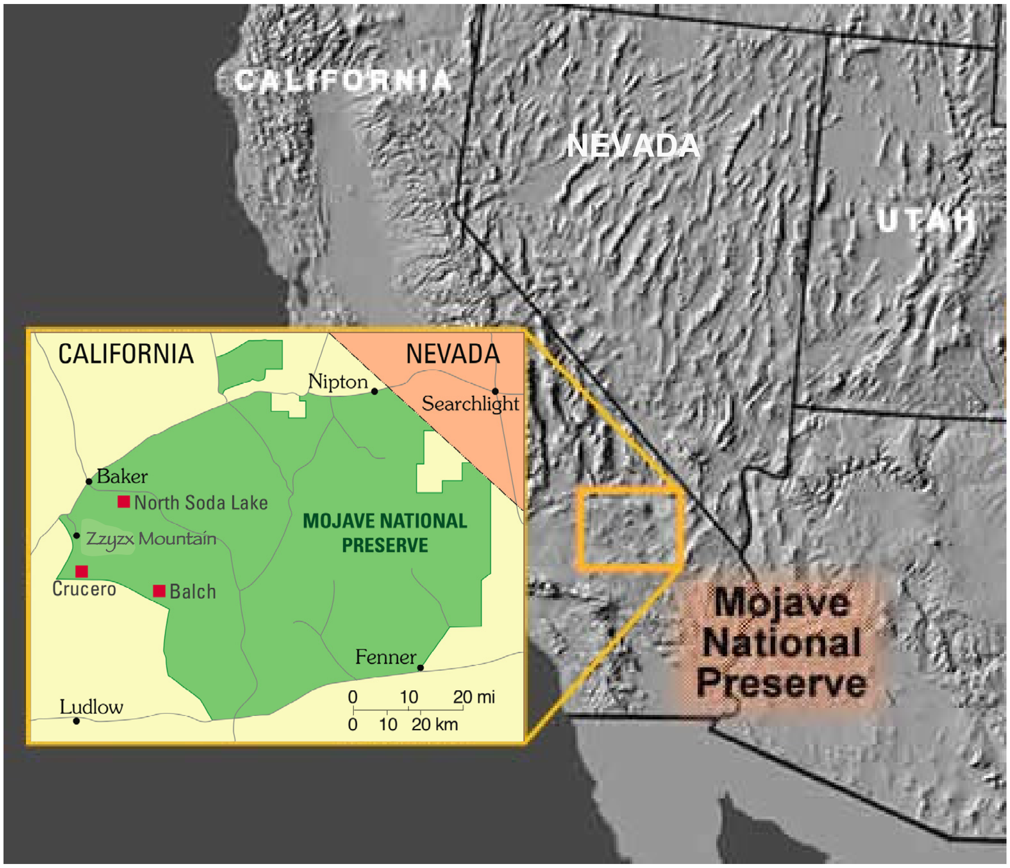
Figure 5. Vegetation coverage (green vertical bars; in percent) at the Balch Site. Total living and dead

annual plants plus debris (sticks and stones); and weight in grams per day of eolian sediment in BSNE collectors (red bars) plotted by year. Length of red bar indicates the collection period of each sample. NS designates (Not in Service), the sensor had not been installed yet.

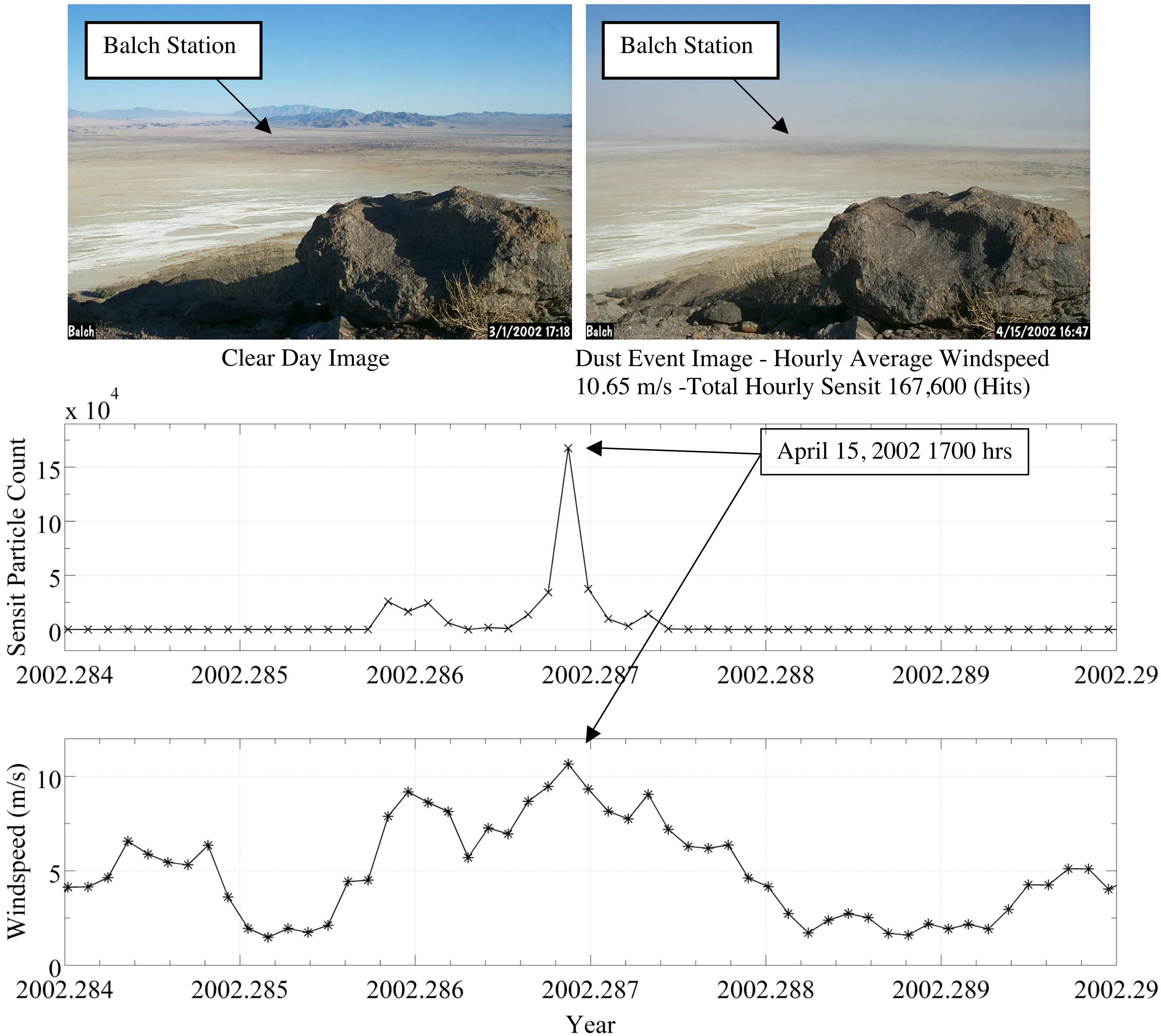
Figure 6. Repeat photographs of the Balch site illustrating the wide variation in annual vegetation cover. Letters correspond to specific time periods indicated in Figures 4 and 5.

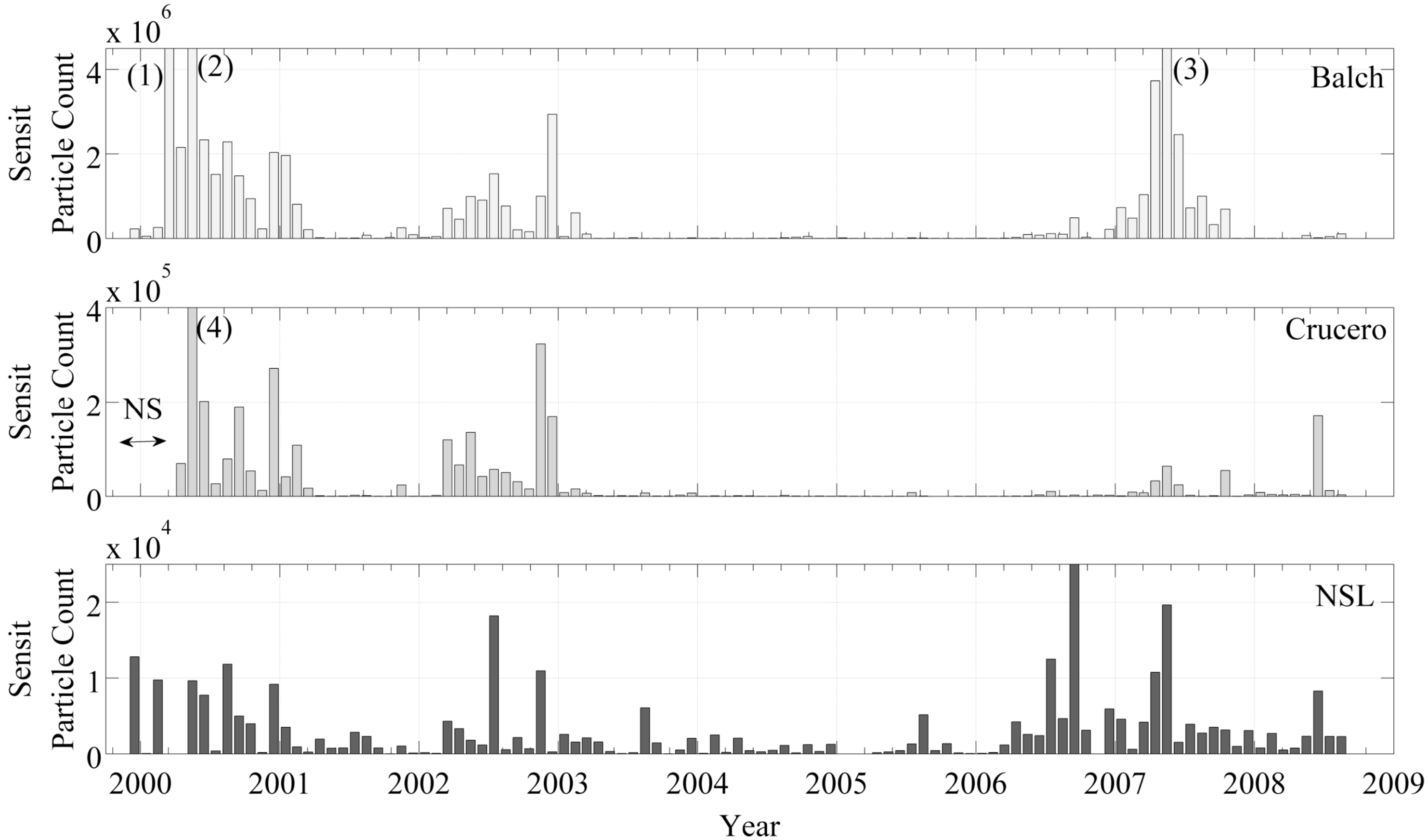
Figure 7. Monthly time series of conditions at Balch including total rainfall, total Sensit particle counts, and average soil moisture. The vertical scale of the total Sensit particle counts has been truncated to show more detail during months of lower saltation activity. Maximum values (of truncated months) are presented in Figure 3. NS designates (Not in Service), the sensor had not been installed yet.

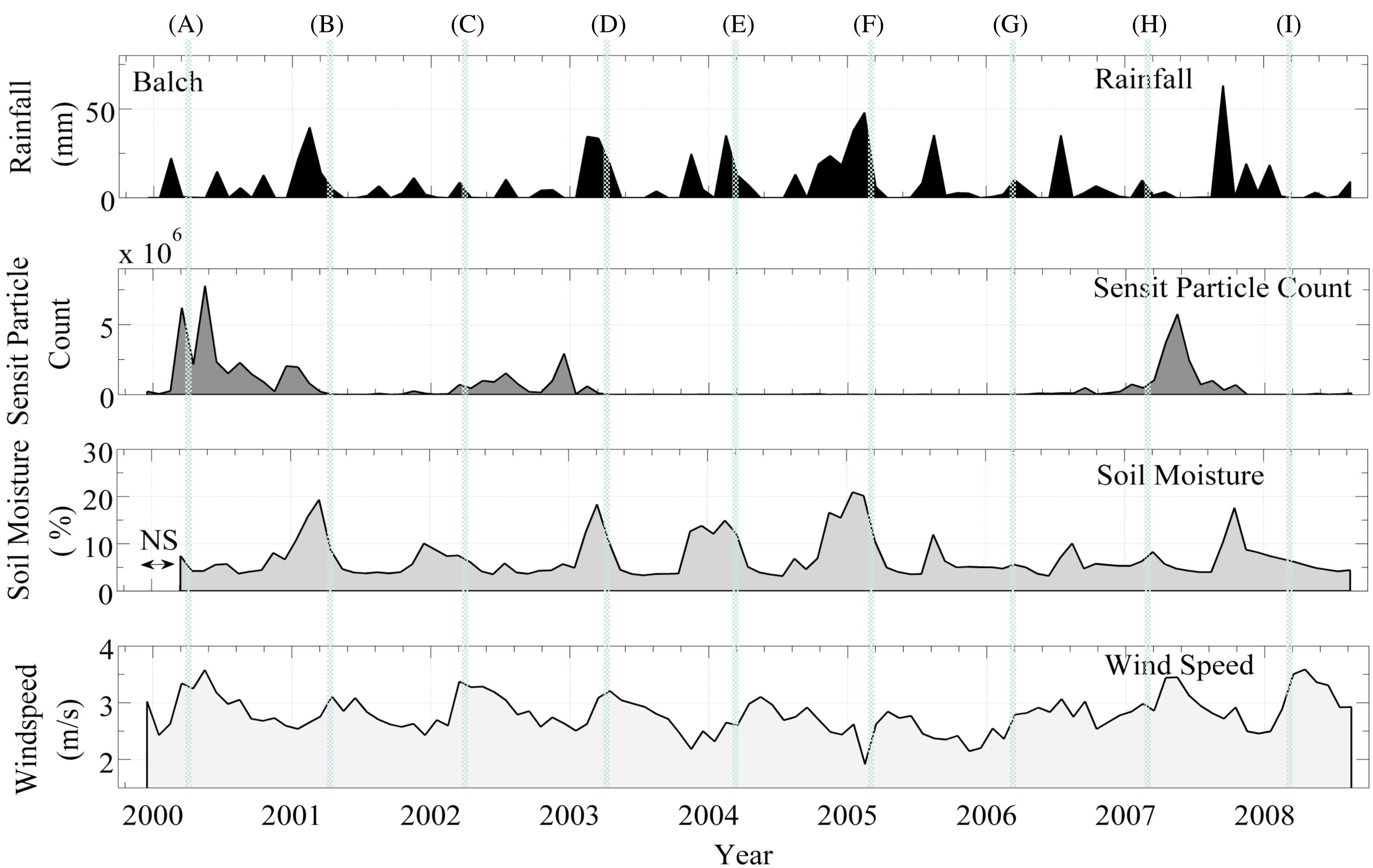
Table 1. Percent coverage summary for annual vegetation at the Balch, Crucero, and North Soda Lake study sites.



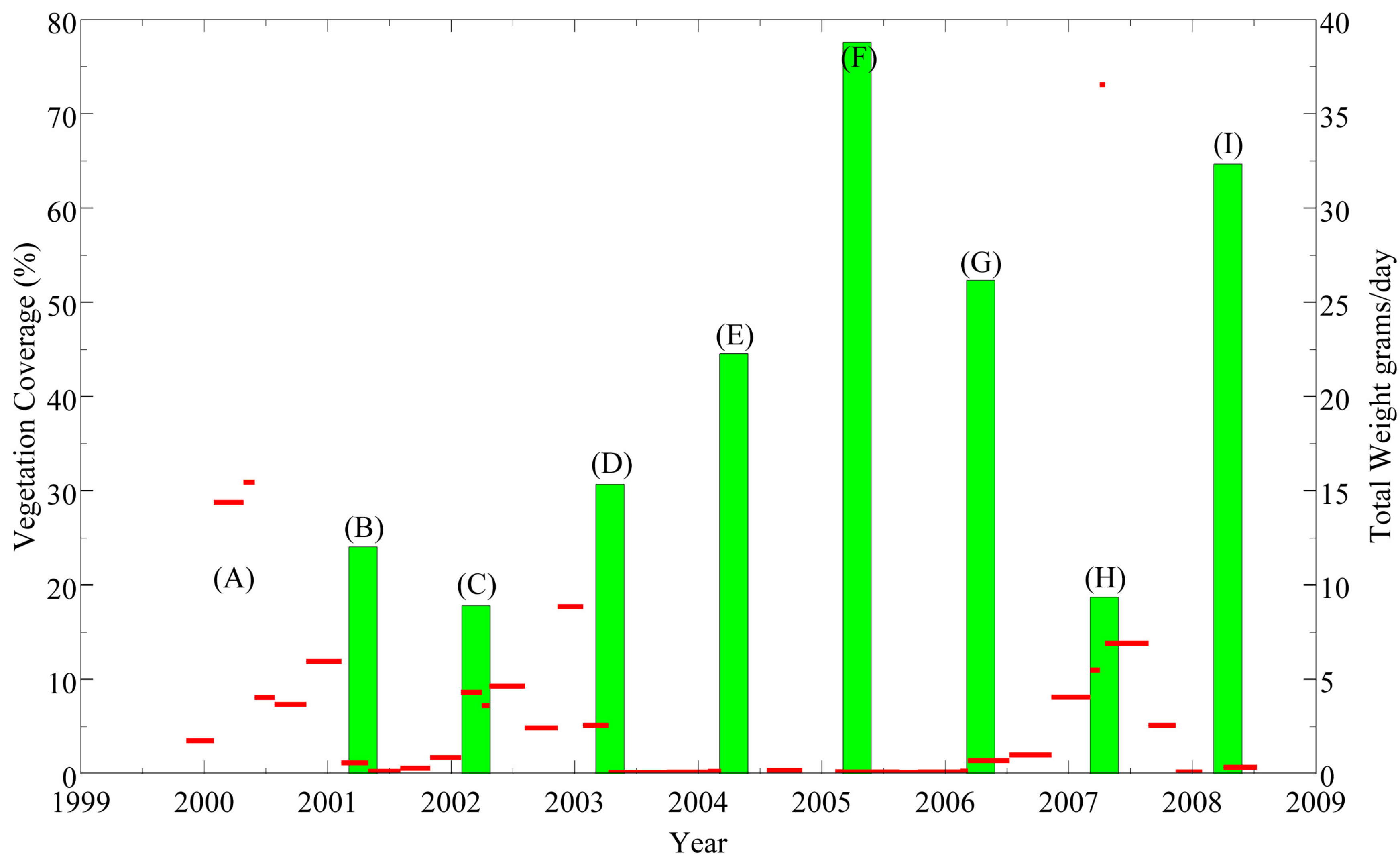
CALIFORNIA
NEVADA
UTAH
CALIFORNIA
NEVADA
Nipton
Searchlight
Baker
North Soda Lake
MOJAVE NATIONAL PRESERVE
Zzyzx Mountain
Crucero
Balch
Fenner
Ludlow
0 10 20 mi
0 10 20 km
Mojave National Preserve

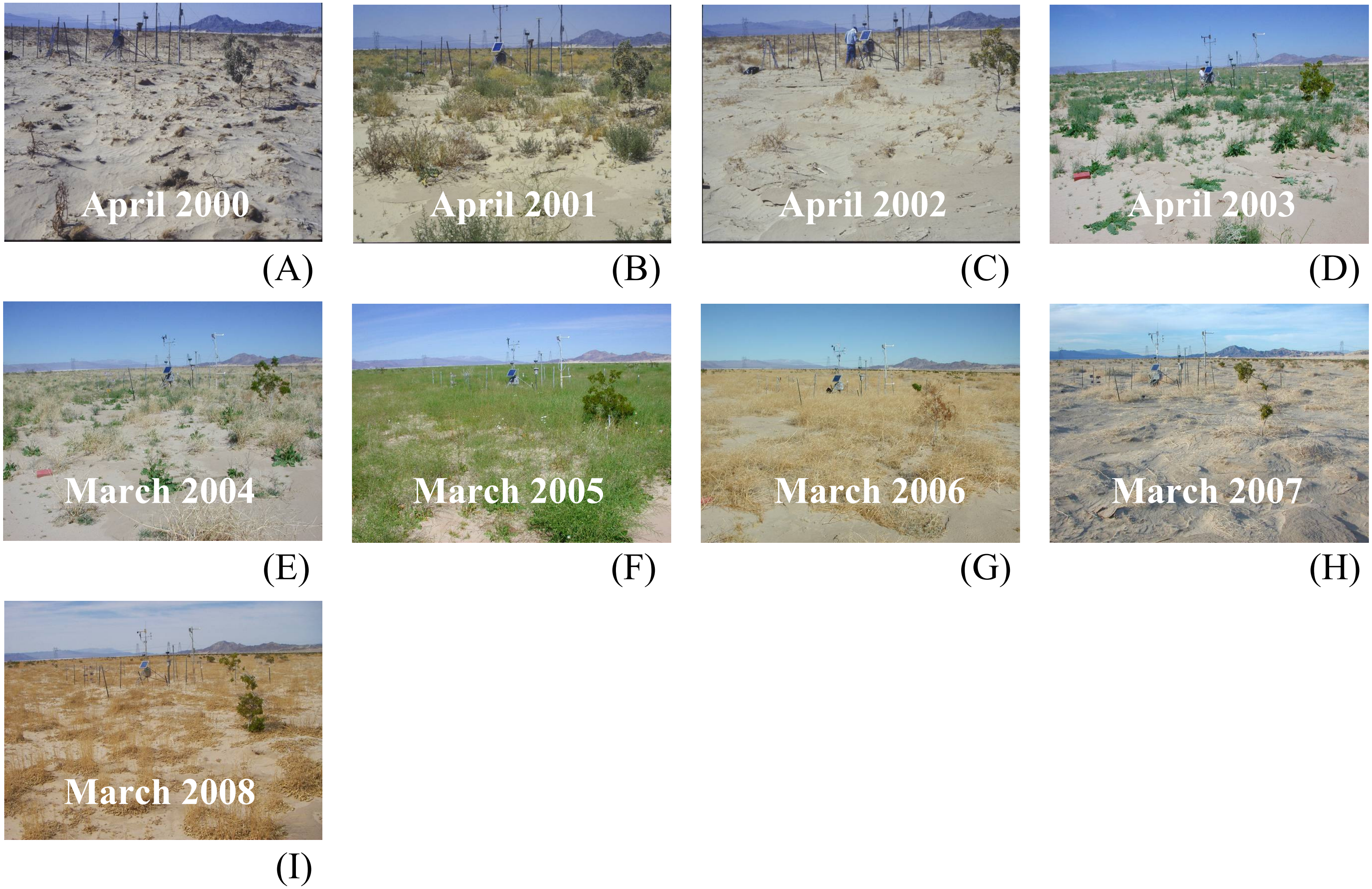

Balch Station
Balch
3/1/2002 17:18
Clear Day Image
Balch Station
Balch
4/15/2002 16:47
Dust Event Image - Hourly Average Windspeed
10.65 m/s -Total Hourly Sensit 167,600 (Hits)
April 15, 2002 1700 hrs
x 10^4
Sensit Particle Count
0
5
10
15
2002.284
2002.285
2002.286
2002.287
2002.288
2002.289
2002.29
Windspeed (m/s)
0
5
10
2002.284
2002.285
2002.286
2002.287
2002.288
2002.289
2002.29
Year


x 10^6
(1)
(2)
(3)
Balch
x 10^5
(4)
Crucero
NS
x 10^4
NSL
Sensit Particle Count
0
2
4
1
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Year



(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
(I)
Balch
Rainfall
Rainfall (mm)
50
0
x 10^6
Sensit Particle Count
Sensit Particle Count
5
0
Soil Moisture
Soil Moisture (%)
30
20
10
0
NS
Wind Speed
Windspeed (m/s)
4
3
2
2000
2001
2002
2003
2004
2005
2006
2007
2008
Year


Vegetation Coverage (%)
Total Weight grams/day
Year
(A)
(B)
(C)
(D)
(E)
(F)
(G)
(H)
(I)
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
40
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009


April 2000
(A)
April 2001
(B)
April 2002
(C)
April 2003
(D)
March 2004
(E)
March 2005
(F)
March 2006
(G)
March 2007
(H)
March 2008
(I)

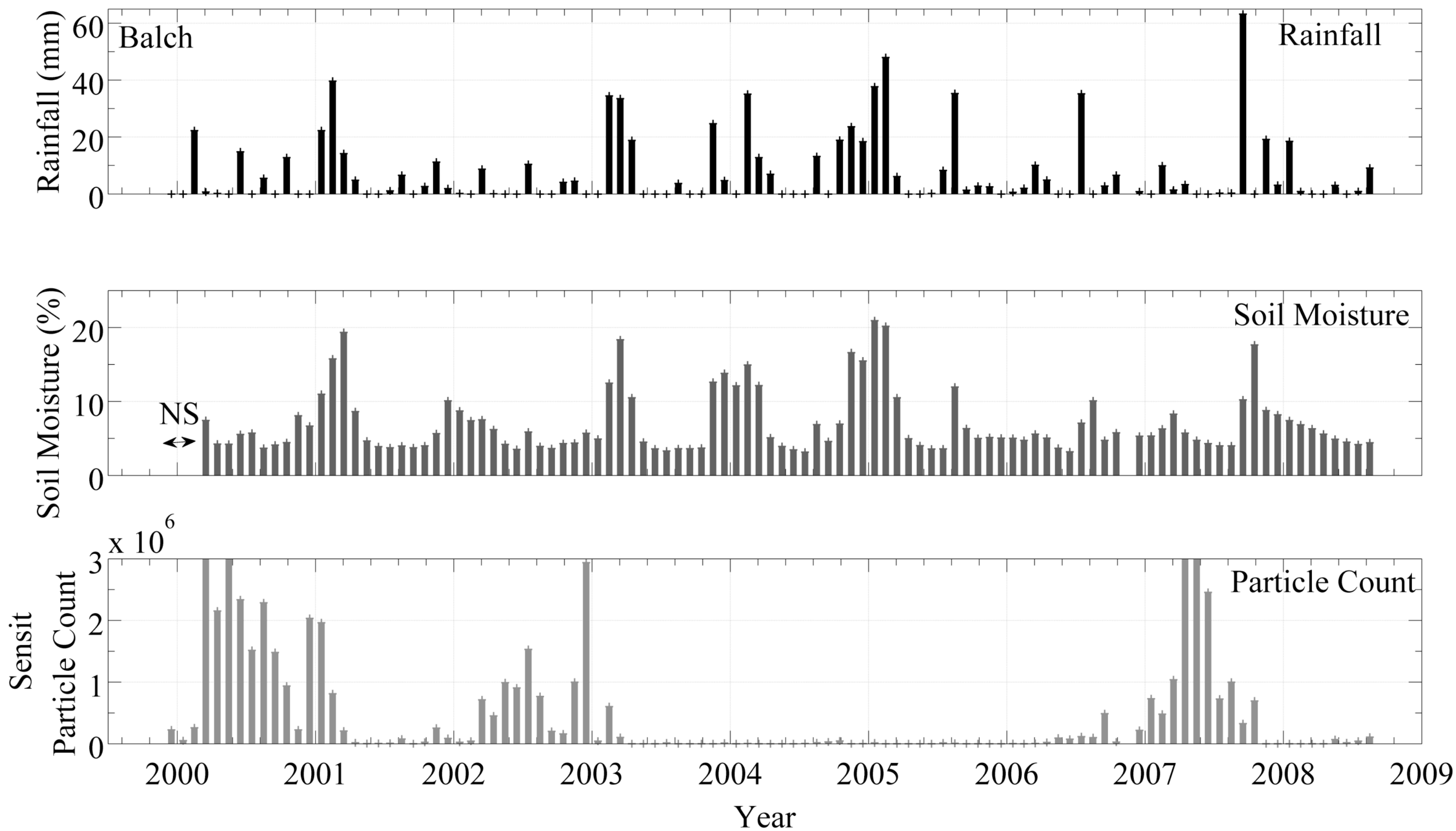

Balch
Rainfall
Rainfall (mm)
Soil Moisture
Soil Moisture (%)
NS
x 10^6
Particle Count
Sensit
Particle Count
Year
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009

Table 1. Percent coverage summary for annual vegetation at the Balch, Crucero and NSL study sites.

	Balch	Crucero	North Soda
Apr-01	23.9 (a)	29.96 (a)	9.34 (a)
	0.04 (b)	2.61 (b)	0.38 (b)
	0.13 (c)	2.13 (c)	1.84 (c)
	24.07 (d)	34.7 (d)	11.56 (d)
Mar-02	1.6 (a)	4.4 (a)	1.61 (a)
	13.75 (b)	17.9 (b)	7.79 (b)
	2.48 (c)	1.34 (c)	1.32 (c)
	17.83 (d)	23.64 (d)	10.72 (d)
Apr-03	20.1 (a)	26.88 (a)	7.8 (a)
	9.65 (b)	1.98 (b)	2.19 (b)
	0.95 (c)	0.85 (c)	1.66 (c)
	30.7 (d)	29.71 (d)	11.65 (d)
Apr-04	19.65 (a)	24.4 (a)	5.78 (a)
	18.84 (b)	5.55 (b)	4.11 (b)
	6.07 (c)	2.2 (c)	1.85 (c)
	44.56 (d)	32.15 (d)	11.74 (d)
Apr-05	77.54 (a)	71.3 (a)	8.1 (a)
	0 (b)	0.05 (b)	2.07 (b)
	0.05 (c)	0.06 (c)	2.15 (c)
	77.59 (d)	71.44 (d)	12.32 (d)
Apr-06	0.56 (a)	0 (a)	0 (a)
	37.1 (b)	52.65 (b)	5.86 (b)
	14.68 (c)	3.05 (c)	1.44 (c)
	52.34 (d)	55.7 (d)	7.3 (d)
Apr-07	0 (a)	0.84 (a)	0.45 (a)
	17.62 (b)	18.21 (b)	3.95 (b)
	1.1 (c)	3.56 (c)	1.28 (c)
	18.72 (d)	22.61 (d)	5.68 (d)
Apr-08	0.81 (a)	0.37 (a)	0 (a)
	61.67 (b)	15.78 (b)	6.32 (b)
	2.19 (c)	4.13 (c)	1.84 (c)
	64.67 (d)	20.28 (d)	8.16 (d)

(a) = living annual plants, (b) = dead but intact,(rooted) annual plants, (c) = sticks, stones, ephemeral debris on the surface, (d) = percentage cover total of (a) plus (b) plus (c).